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PERFORMANCE EVALUATION OF JOINT COOLING AND IN-
FORMATION TRANSMISSION FOR ON-BOARD COMMUNICA-
TIONS

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ABSTRACT

ANNA VOLKOVA: Performance Evaluation of Joint Cooling and Information Transmission for On-Board Communications

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Progress of hardware components provides the growth of computer performance approximately every decade. Along with increasing complexity of computer components, there is also the trend to miniaturization. All these imply the need in new ways of components interconnections with efficient interface communications inside modern computers. On the other hand, the progress of hardware components and miniaturization result to the rise of heat release. New ways of cooling are constantly developing for modern computers, including laptops, tablets and smartphones. However, not all of them are efficient enough.

Having communications and cooling systems separately often makes it impossible to miniaturize a computer device. In order to succeed in this direction, the combination of both systems is needed. The new system should not only allow the hybrid design, but also provide efficient cooling and information transmission.

In this thesis, the statement of efficient joint cooling and information transmission is described. System design, the choice of necessary materials, properties of signal propagation and performance evaluation of the results for cooling and data transfer are provided in the thesis.

It is shown that the terahertz frequency range is the most suitable for the information exchange between hardware components as it could provide extremely high data rates. However, it requires specific conditions for proper performance including non-absorbing materials.

A system based on heat pipes is proposed. The heat pipes, working as a cooling system as well as a waveguide, have cooling medium inside and metal casing. Cooling medium and metal casing should satisfy both cooling and transmission requirements. The best choice of cooling medium is a refrigerant, especially isobutane, as it does not have absorption and provides the best cooling properties. The best casing is copper as it ensures good reflectivity for the propagated signal and thermal conductivity for the heat transfer.

The results of the cooling evaluation are reached through MATLAB software calculations. Transmission performance is calculated in the COMSOL Multiphysics simulation software. The results prove that the materials are chosen right and the system is efficient for the use in modern computers.

PREFACE

This work has been done in the Nano Communications Center, the department of Electronics and Communication Engineering in Tampere University of Technology, Tampere, Finland in 2015.

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LIST OF SYMBOLS AND ABBREVIATIONS

AMD	Advanced Micro Devices, Inc.
B2B	Board-to-Board
CFC-11	Chlorofluorocarbon-11
CPU	Central Processing Unit
EM	Electromagnetic
GPU	Graphical Processing Unit
GWP	Global Warming Potential
HT	HyperTransport
IEEE	Institute of Electrical and Electronics Engineer
IG THz	Interest Group Terahertz
MAC	Media Access Control
ODP	Ozone Depletion Potential
OWC	Optical Wireless Communications
PC	Personal Computer
PCIe	Peripheral Component Interconnect Express
p.s.d.	power spectral density
QPI	Quick Path Interconnect
RF CMOS	Radio Frequency Complementary metal–oxide–semiconductor
SDRAM	Synchronous Dynamic Random Access Memory
SNR	Signal-to-Noise Ratio
TG	Task Group
TDP	Thermal Design Power
THz	Terahertz
UWB	Ultra-Wide Bandwidth
WPAN	Wireless Personal Area Network

A	magnetic vector potential
A_{ch}	channel cross-sectional area [m^2]
A_{CPU}	surface area of a CPU [m^2]
B	channel bandwidth [Hz]
B	magnetic flux density [Wb]
$C(d)$	channel capacity [b/s]
C_p	heat capacity [J/kg K]
c_0	speed of light [m/s]
D	electric flux density [C/m^2]
D_H	cylindrical channel diameter [m]
d	distance between transmitter and receiver [m]
E	electric field [V/m]
E_{TDP}	peak heat energy generated by a core [W]
f	operating frequency [Hz]
H	magnetic field [A/m]
J	current density [A/m^2]
$K(f)$	absorption coefficient [$1/\text{m}$]
$k(f)$	extinction coefficient
k_B	Boltzmann constant [J/K]
κ	thermal conductivity [$\text{W}/(\text{m}\cdot\text{K})$]
$L_A(f, d)$	molecular absorption loss [dB]

L_{ch}	contact length of the channel with the CPU surface [m]
$L_P(f, d)$	free-space propagation loss [dB]
N_A	Avogadro constant [mol ⁻¹]
$\tilde{n}(f)$	complex index of refraction
$n(f)$	real part of complex index of refraction
$Q_{G,I}$	volume density of molecules [molecules/m ³]
p	pressure of a medium [Pa or mmHg or N/m ²]
p_0	standard pressure [mmHg]
$P_N(f, d)$	p.s.d. of molecular absorption noise [dB/Hz]
P_{Rx}	p.s.d. of the received signal [W/Hz]
P_{Tx}	p.s.d. of the transmitted signal [W/Hz]
R	gas constant [J/K·mol]
$R(\omega)$	reflectivity
Re	Reynolds number
T	temperature of a medium [K]
T_0	standard temperature [K]
T_E	equilibrium temperature [°C]
ϑ	average velocity of the fluid [m/s]
V	electric scalar potential
W_{ch}	contact width of the channel with the CPU surface [m]
ϵ_0	permittivity of vacuum
$\epsilon_r(\omega)$	relative permittivity
ϵ_b	contribution from bound electrons
μ_0	permeability of vacuum
$\mu_r(\omega)$	relative permeability
ν	kinematic viscosity [m ² /s]
ρ	density of the fluid [kg/m ³]
$\sigma_{G,I}$	cross-section absorption [m ² /molecule]
σ	electrical conductivity [S·m ⁻¹]
δ	skin (penetration) depth [nm]
τ	relaxation time [s]
ω	angular frequency [rad/s]

1. INTRODUCTION

1.1 Communications types

Modern computers based on integrated circuits are hundreds of times less in size and millions of times more efficient than the early machines. Such progress became possible due to invention of integrated circuits and the following increasing of their number and complexity inside the computer components. Providing efficient communications between computer components (e.g., Central Processing Unit and Graphical Processing Unit) is of importance in order to have sufficient data rates and rational networking. The conventional way to connect intra-computer components is the use of multilane buses. However, they are not effective enough anymore due to components progress. First, buses require large physical space what is problematic in the worldwide trend to miniaturization. Secondly, they already cannot provide the appropriate data rate even by the modern interfaces such as PCI Express. One way to increase the communication rate is to use advanced coding techniques [27]. However, the new ways for efficient communications are needed in order to satisfy the computer progress requirements.

Nowadays, wired and wireless proposals exist for intra-computer communications as well as for on-board communications. By intra-computer communications, we mean the conventional point-to-point way of connection between components. On-board communications is a new paradigm for computer chip-to-chip communications. It allows information transmission between the main components, such as CPU and GPU, by means of transmitter and receiver installation directly on the printed boards.

Wired solutions are mostly based on fiber optic technology where traditional metal (aluminum or copper) wiring between components is replaced with more efficient fiber-optic cables. Such cables carry information signals using pulses of light instead of electrical signal in metal wires. In spite of the expensive cost, the use of these cables increases due to extremely high data rates. Besides, fiber optics is less susceptible to electrical interference and requires less power. Fiber optic technology is also suitable for on-board communications. Graded-index core polymer optical waveguides were presented in [15] for optical on-board interconnections. However, except the price, fiber optics is limited from widespread use for computer components communications due to complexity of networking between them. Active research is directed to make optical multiplexers and optoelectronic converters in smaller dimensions as it allows to reduce the required space, e.g. in [23] compact multi-fiber receptacle has been developed for on-board communications what enables to achieve dense fiber connection.

On the other hand, wireless chip-to-chip communications allows having significantly lower network complexity, system miniaturization [14] and enables broadcasting and multicasting capabilities. However, existing wireless systems (WiFi, Bluetooth) provide significantly lower interface capacity than wired systems. Moreover, the efficient medium access control is still needed to be developed for the open space wireless systems. The hot research topic nowadays is the usage of antennas at the 60 GHz wireless spectrum, which is between approximately 57 GHz and 66 GHz. Broadband signal up to 9 GHz allows getting high data rate for a short range communications with excellent interference immunity. Operating frequency of 66 GHz for chip-to-chip and intra-chip wireless communications allows for bigger absolute bandwidths; besides, the state of the art RF CMOS technology maintains operation in that frequency range [28]. Another tendency is the optical wireless communications (OWC). OWC systems enable wireless connectivity using infrared, visible or ultraviolet bands. They typically offer a cost-effective protocol-transparent link with high data rates and utilize laser transmitters [25], [13]. The ultra-short range OWC systems are suitable for chip-to-chip communications as they provide broadband services, easy deployment and no license requirement [11]. Due to these advantages, the OWC systems were developed at the beginning of the last century. However, the interest on them decreased as the experiments did not promise any baggage of technological development. Moreover, electromagnetic waves at optical frequencies interact with the atmosphere stronger than the microwave waves [22]. All these, as well as the fact that short-range OW systems with point-to-point links work at distances typically limited to a few tens of millimeters, make the OWC inapplicable for the on-board communications at the present time.

The last promising trend is the communications at the terahertz frequencies. Communications at the terahertz frequency range 0.1 – 10 THz has several advantages including ultra-wide unlicensed bandwidth and non ionizing radiation. Such UWB gives the opportunity to achieve extremely high capacity over the distances up to one meter [4]. The absence of ionizing effects makes the THz radiation biologically innocuous and, thus, suitable for mass-market usage. The only drawback for communication purpose is that the THz radiation is absorbed by water and water-containing substances (e.g., humid air). This makes inefficient the use of THz communications in open space environment with water vapor molecules.

1.2 On-board communications

Typically used nowadays buses communications requires significant amount of wires, complex networking between components and, moreover, does not provide essential interface capacity, while hardware components become more and more powerful. The same situation one can observe with optical communications except providing significantly higher capacity. However, price and the need in appropriate optical multiplexers and optoelectronic converters limit widespread use of fiber optics.

The most effective communications could be the above mentioned on-board communications used for component-to-component connections inside a computer. This study is performed under the umbrella of Board-to-Board (B2B) communications [12] and standardized by IEEE 802.15. IEEE 802.15 is a communications specification provided by the Institute of Electrical and Electronics Engineers (IEEE) IEEE 802 standards committee for wireless personal area networks (WPANs). The IEEE 802.15 Working group aims on the development of standards for WPANs and short distances wireless networks. Such networks address wireless networking technology of portable and mobile computing devices such as PCs, peripherals, cell phones, and other electronics, allowing these devices to communicate and interoperate with each other. The IEEE 802.15 Working group is divided into two major categories TG4 (low rate) providing data rates of 20 to 250 Kbps and TG3 (high rate) supporting data rates up to 55 Mbps. The IEEE 802.15.3 Task Group 3c (TG3c) formed in March 2005 operates with the millimeter-wave networks and provides data speed up to several Gbps.

One way of on-board communications is wireless technology which allows getting rid of wires and saving physical space. The major shortcoming of wireless communications is significantly low interface capacity. Besides, wireless signal could be easily blocked by other components or have essential interference with other devices. All these make the wireless solutions not very attractive for the use in this particular field.

In 2008 IEEE 802.15 created the THz Interest Group (IG THz) focused on THz communications and related network applications operating in the THz frequency range between 275 – 3000GHz. Such THz communications would provide wireless modulation methods of limited complexity and offer very high data rates in multiples of 10 Gbps, and up to possibly 1 Tbps. THz applications include component to component, board to board, machine to machine, human to machine and human to human, wireless communications [9]. THz communications is suitable for short distances (few centimeters) with extremely high data rates (a few Tbps) as well as for longer distances of several kilometers but with lower data transfer rates. Such data rates make the THz communications very attractive for chip-to-chip interconnections and research under the B2B communications is a hot topic nowadays.

THz communications requires special conditions for the effective information transmission and could not be used in the open space as it contains water vapor molecules absorbing THz radiation. The solution could be the use of waveguides with certain non-absorbing medium. Such approach would provide the possible data rates of THz communications up to 1 Tbps. Besides, the system could be combined with the cooling system inside the computer as we have pipes (waveguides) which could be filled by special cooling fluid. In spite of the fact, that THz communications has lower capacity capabilities than optical one, it would allow joining two functionalities in one system and, thus, saving physical space in a computer.

1.3 Cooling system types

Besides components interconnections, increasing the complexity of computer components leads to rise of heat release. Thus, the efficient cooling of electronic components is another challenge for modern computers. Computer cooling should provide the removing of redundant heat produced by hardware components in order to keep the temperature of components within permissible operating temperature limits. Typically, cooling scheme divided into two groups: 1) reducing the ambient temperature within a computer casing 2) cooling an individual component or a small surrounding area. Computer components which commonly cooled individually are CPU, GPU and the north-bridge.

Early personal computers were able to use only passive cooling by natural convection. A passive heat-sink cooling implies attaching a block of metal to the part that requires cooling. Metal is used because its heat conductivity is higher than that of air, so it radiates heat better than the component that needs cooling. A historical solution for a desktop computer was fan-cooled aluminium heat sinks. Now such sinks usually include copper.

While passive cooling produces no fan noise and needs no extra power for cooling system, it can be not sufficient for modern computers.

Modern hardware components are usually designed to generate as little heat as possible. Besides, computers and operating systems may be designed to decrease power consumption and, consequently, heat generation according to workload. However, there is still more heat that can be produced than that can be removed without additional cooling system.

The so-called Thermal Design Power (TDP) describes the maximum amount of heat, generated by the component that should be dissipated by the cooling system. The increasing the complexity of hardware components influences on the TDP value. Growing TDP requires efficient cooling system.

Different solutions and their combinations, including mechanical fans, water-cooling systems, metallic pipes and other methods, are used in laptops and personal computers (PCs), depending on the TDP parameter and available physical space. Water-cooling systems and other liquid systems are mostly used in stationary computers with high-performance CPUs and GPUs. Typically, it is powerful machines with special software for simulations tasks or gaming computers. However, water cooling has a number of drawbacks, including installation difficulties, the need in good isolation and significant physical space. Liquid cooling is normally combined with air cooling: liquid cooling for the hottest components (CPUs, GPU) and air cooling for other components. The only fan is almost not applicable as it is not efficient any more. At least the combination of

several fans is utilized if physical space is enough for that. Laptops utilize combination of fans and heat sinks based on the metallic pipes. In computers, heat pipes are normally used for CPU cooling. The heat sink on the CPU is attached to a larger radiator heat sink, and together they form a large heat pipe. The radiator is cooled using some conventional method. Overall, heat pipes are expensive and usually used if space is tight (in small computers and laptops) or fan noise is not acceptable (audio). Also, many desktop CPUs and GPUs use heat pipes because of the efficiency of this method. However, such cooling of laptops is still not kept pace with the components progress as well as the miniaturization requirements. The new efficient methods are required for cooling of modernly equipped computer.

1.4 Problem definition

In order to avoid difficulties of complex networking for signal transmission and additional cooling equipment, we propose to build the one system with simultaneous cooling and information transmission. Besides, such system allows reducing the physical space and, hence, miniaturizing the devices where it would be installed. Terahertz frequency range is chosen for data transfer due to attractive properties of the THz radiation for short distances. However, such radiation has absorbing property, which should be taken into account when choosing cooling medium and other materials of the system.

The system should take advantages of cooling system and be applicable for information transmission. Waveguides, filled with specific cooling substance in order to serve as the heat pipes, should be used for data transfer. Materials of the system should be chosen in order to provide the best possible signal propagation and simultaneous heat dissipation from the components. The thesis provides particular solutions for all system elements including waveguide design, the cooling medium, and estimation of the system performance with respect to both cooling and transmission functionalities.

1.5 Thesis Outline

The core of this thesis is the performance evaluation of joint cooling and information transmission for on-board communications. In order to provide the results, the following tasks should be solved:

- system design including waveguide design and cooling system design;
- heat pipe design including casing material of a pipe and cooling medium;
- heat transfer calculations;
- EM simulations.

The thesis is organized as follows: Section 2 presents the conceptual design of the proposed system, the design of the cooling system and detailed properties of the terahertz radiation for information transmission. Section 3 describes the choice of components for

the system. Section 4 demonstrates results of cooling and transmission performance. Finally, the last section discusses several conclusions and future research possibilities.

2. THE CONCEPTUAL DESIGN

2.1 The proposed system

The conventional wired, on-board wireless and proposed designs for communication system of the laptop motherboard are conceptually illustrated on Figures 1-3. Figures show communication interfaces among various devices residing on or connected to the motherboard in addition with cooling system used in modern laptops. The cooling system is usually represented by one or several fans and special metallic (typically, copper) plates going through a number of main components needed to cool down (usually, CPU and GPU). This cooling system is very popular nowadays for laptops, however, not enough efficient for the newest models which are too small or too powerful.

Figure 1 demonstrates the conventional system design with point-to-point wired interface and the described above cooling method. Wires are illustrated conceptually, as there are significantly more wires in the real system. The main drawbacks of such system are the huge amount of wires, not efficient speed transmission (in the case of buses connection) and heat transfer.

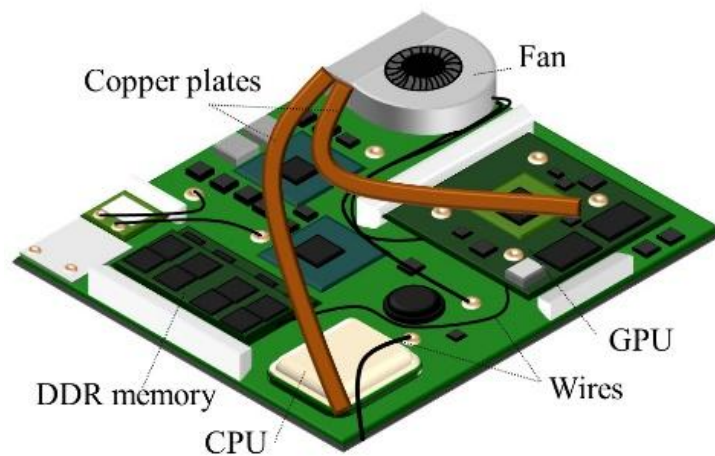


Figure 1. Conventional wired system design.

Figure 2 shows wireless architecture with chip-to-chip communications between components. The cooling system is the same as for the previous case. Such architecture requires significantly lower physical space. However, speed transmission is lower than in wired systems and the cooling system is also not efficient.

In the case of open space wireless architecture, efficient MAC scheme is required, if all interfaces utilize the same frequency band. Alternatively, different frequencies could be used. The main drawback of this architecture is insufficient bandwidth utilization at the air interface. Interfaces of modern computers require extremely large rate characteristics. Considering the connection of hardware components in wired systems, Quick Path Interconnect (QPI) and HyperTransport (HT) interfaces used by Intel and AMD, respectively, provide the rates of up to few hundreds of Gbps (400Gbps over 20+20 lanes when operating at 3.2GHz), depending on the used clock. QPI developed by Intel is used for point-to-point processor interconnect and replaces the front-side bus in modern CPUs. HT is a point-to-point link for AMD CPUs interconnection and the associated Nvidia motherboard chipsets. At the other hand, PCI Express is an interconnection bus, allowing the addition of extension cards in the computer. The connection between two PCIe devices is called a link, built from one or more lanes. PCIe v4.0 interface which was standardized in 2015 offers 15.755Gbps per lane and up to 252.064Gbps in 16-lanes slots using aggressive 128b/130b encoding [1], [8]. Consequently, the capacity of wireless communications at frequencies lower than few tens of GHz is inappropriate to compete with state-of-the-art wired solutions. Moreover, the need of licensing a certain frequency spectrum for this architecture due to interference from other communications technologies is an additional problem, which may prevent from using the wireless scheme.

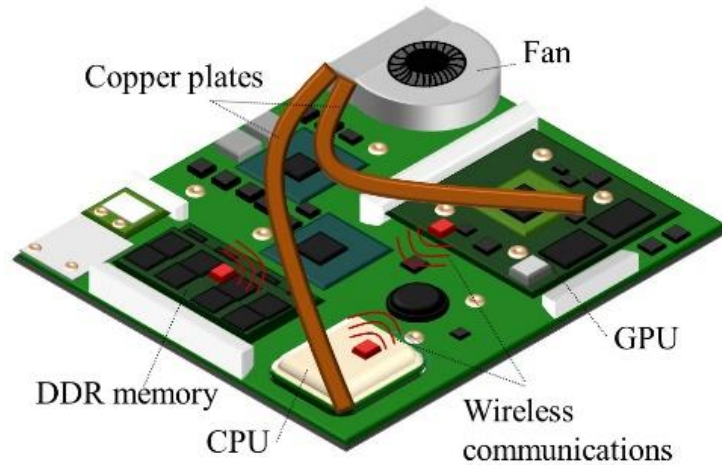


Figure 2. *Wireless system design.*

To cope with the above-mentioned issues, we propose the architecture, presented in Figure 3. We assume that heat pipes are going through the main hardware components, which need to be cool down and have information to transmit. This design combines heat pipes functionality with information exchange between the chips via the same medium. The proposed solution could be classified as wireless due to the use of so far not very well explored 0.1–10 THz frequency band. However, the design is conceptually similar to the optical one because of requiring some specific waveguides to enable

communications between nodes. Waveguide is a hollow tube where wavelength approaches the cross-sectional dimensions of the waveguide. The heat pipe works as a waveguide to ensure the absence of interference in the communication system. The selected THz band is of special importance, as the system may not require band licensing for this special type of communications. On top of this, the effect of THz radiation on silicon based equipment is not fully understood. Covering of propagation paths guaranteed that this radiation does not affect the functionality of modern computer components.

The casing if the waveguide is metallic. Waveguide's inner cavity is filled with specific refrigerant having no absorption lines in the THz band in order to ensure that the propagation of THz waves is not affected by molecular absorption inherent for water and water vapor molecules. Therefore, refrigerant should provide two main functions: (i) cools down the environment in between communicating components and (ii) ensures optimal propagation conditions for THz waves.

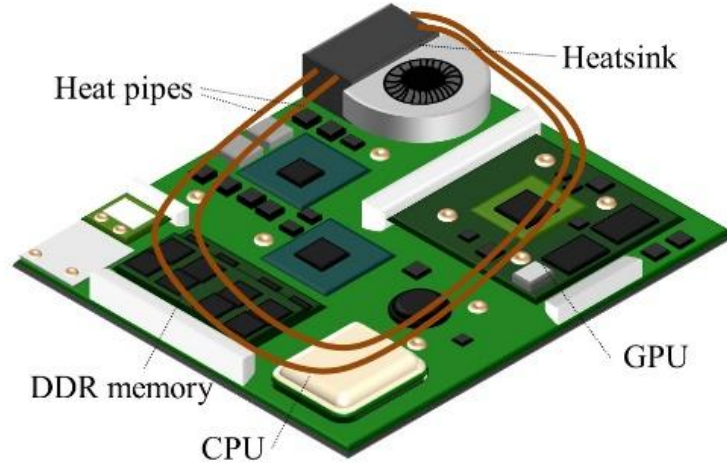


Figure 3. *The proposed system design.*

It is important to note that the proposed system and optical design are characterized by similar drawback. It is the need of complex multiplexers to enable networking between more than two components connected directly. Therefore, both systems are best suited for establishing point-to-point communications links. When the number of devices that need to communicate increases, instead of creating a full mesh network between them, one could rely on a star-based architecture with multiplexer at the center. However, in addition to just providing communications between components, our system allows for cooling of them. How to build the cooling system is described in the next section.

2.2 Cooling system design

There are several possible ways to build the system to cool down the hardware components. Modern computer components are already designed to produce very little heat, but despite of that cooling is still an important subsystem. At present time, it can be air cooling by fans, water cooling including active and passive systems, liquid submersion cooling by special oils, phase-change cooling usually by refrigerants, metallic pipes and heat sinks and some other methods. These methods are distinguished by the available physical space and system complexity, reliability, amount and speed of cooling, noise, price, and other characteristics. The short description of the major methods is presented below.

The most popular approach is air cooling and, first of all, computer fans. A fan can be installed for the whole case of the computer or be dedicated to a specific component such as CPU, graphics card, chipset. Less commonly, fans are used for hard drive, optical drive, expansion slot or RAM. The most common type are axial-flow fans. They have blades that force air to move parallel to the shaft about which the blades rotate. Other used types are centrifugal and cross-flow fans. Centrifugal fans are usually quieter than axial fans of the same size and produce more pressure for a given air volume. Computer fans can be combined with passive cooling by heat sinks.

Liquid submersion cooling is done by submerging the computer's components in a thermally, but not electrically, conductive liquid. This type of cooling is rarely used for personal computers but it is a normal method for large power distribution components like transformers, and it is also popular for data centers. The liquid must have low electrical conductivity because it should not interfere with the normal operation of the computer. However, if the liquid is somewhat electrically conductive, it still may be used for insulated components. The most popular liquids for cooling are transformer oils and other oils. Non-purpose oils, including cook oils, can be used for personal computers.

Thermoelectric cooling is based on Peltier effect - direct conversion of temperature differences to electric voltage and vice versa. Thermoelectric cooling element usually contains two unique semiconductors. One is n-type and the second p-type because they need to have different electron densities. The semiconductors are placed thermally in parallel and electrically in series: n-p-n-p-n-p. They are joined with a thermally conducting plate on each side. A voltage is applied to the free ends of the semiconductors and causes a flow of current across the junction of the semiconductors. This leads to a temperature difference. Thermoelectric cooling normally gives up to 70°C between hot and cold sides. The more heat moved, the less efficient works the cooling element, because it needs to dissipate both the moved and generated heat. Peltier junctions give only 10-15% of efficiency of the ideal refrigerator, while conventional compression cycle has 40-60%. So, thermoelectric cooling is used when pure efficiency is less important than solid state nature: no moving parts, compact size etc. Other advantages of

Peltier cooling are invulnerability to leaks (because there is no circulating liquid) and very long life.

Chip-integrated technique is efficient cooling of the hot spots. Conventional cooling has some thermal resistance because the cooling component is placed outside of the hot component. Chip-integrated cooling directly cools hot spots within the package of the chip. Nowadays, power dissipation at hot spots is over 300 W/cm^2 while a typical CPU is less than 100 W/cm^2 . Chip-integrated cooling is essential for developing high power density chips. This technique has two variants: micro-channel heat sinks and jet impingement cooling.

Soft cooling is done by special software which uses CPU power saving. The software issues halt instructions to turn off unused CPU subparts or put them in standby state. Another approach is underclocking, also known as downclocking: CPU timing settings are modified to run at a lower clock rate. Underclocking can be applied to CPU, GPU or RAM. Soft cooling results in lower total productivity but improves user experience because it prevents from noisier cooling technologies such as fans. Strictly speaking, this is not a cooling but a reduce of heat creation.

There are several approaches that do not require dedicated cooling components or software. First, less powerful components can be used. It implements less features (but has all required functions) and generates less heat. Next, the same CPU or any other component can run with voltage below the device specification (undervolting). The processor will not function correctly below a certain voltage; however undervolting usually does not lead to hardware damage. Digital circuits based on metal-oxide-semiconductor field-effect transistors use voltages at circuit nodes for representing logical state. Voltage is switched between low and high. Each node has a certain capacitance. The higher capacitance, the longer it takes to switch between voltages. Higher voltage applied to the circuit allows changing node state more quickly which leads to faster operations. Undervolting, from the other hand, reduces this operation frequency, but also reduces temperature and cooling requirements.

Considering the proposed transmission design, the system should work with cooling fluid, possibly, refrigerants, and have metallic casing of a pipe in order to serve as a waveguide.

The phase-change cooling system uses freons and other refrigerants. However, such system is not suitable for our purpose, as it requires powerful system to cool down the gaseous refrigerant to the liquid state. Besides, phase transition from liquid to gaseous state and vice versa leads to heavy condensation and requires proper insulation of the components' surfaces and, hence, makes impossible the installation of antennas for the transmission purpose.

The system served for our purpose can be built by combining the liquid active cooling system and heat pipes. Heat pipe is efficient though expensive technique. Heat pipe represents a hollow tube with heat transfer liquid inside. Material of a tube should have high enough thermal conductivity and be compatible with the working fluid. Usually, copper or aluminum is used. At the hot end of a pipe, liquid turns into a vapor absorbing heat from a hot element, vapor travels to the other end of a pipe which is cooler so that the vapor condenses giving up its heat and turns into a liquid again. Liquid circulates in the pipe by means of gravity or capillary effect. Such systems are used where physical space is limited (e.g. laptops), or right on the components (e.g. for CPU cooling). However, this system alone does not suit our design, as it works with two-phase state of a medium while we work only with gaseous state of the refrigerant. Thus, the idea of working process of a heat pipe should be taken and combined with the liquid active cooling system.

Liquid cooling is an inversion of a scheme of an insulated component submerged into water. It is highly effective since water has high specific heat capacity and thermal conductivity in compare to air. A typical (active) liquid cooling system consists of a water block, a water pump, a reservoir, a heat exchanger (radiator) and connected pipes (see Figure 4). A pump serves for circulating of a working fluid. A water block takes out the heat from the cooled element to the working fluid. It can be mounted on the CPU or additional components as GPU and northbridge. A reservoir is needed for compensation of thermal expansion of the liquid, increasing the thermal inertia of the system and improving the ease of filling and draining the working fluid. A heat exchanger serves to move heat from a working fluid into air. Usually, it uses a radiator with a fan attached. In order to cool the circulating fluid below the ambient air temperature, liquid cooling system may use: i) thermoelectric cooling – systems, where liquid is cooled directly by the evaporator coil of a phase change system, or ii) to place a thermoelectric element called Peltier junction between the heat-generating component and the water block. The major shortcoming of liquid cooling are the potential coolant leak and overall complexity.

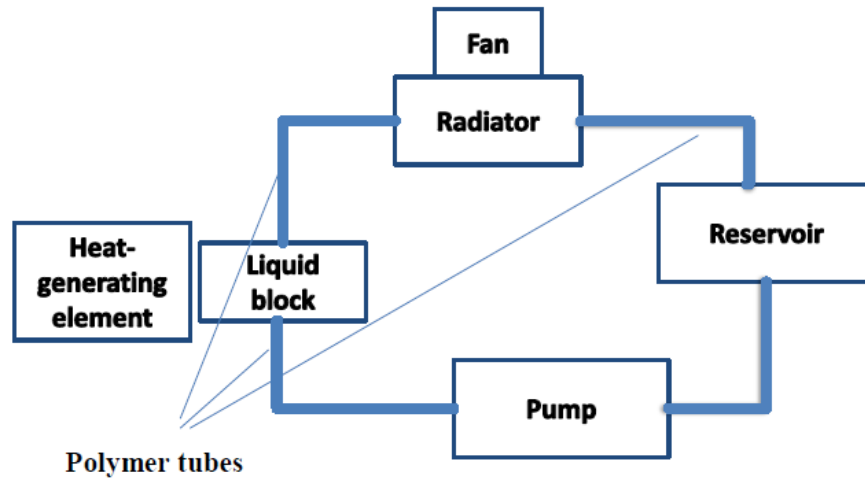


Figure 4. Typical water cooling system.

For our design, presented in Figure 5, we need some heat exchanger (the exact model is out of the scope of this thesis) and a pump. Instead of usual polymer tubes, we use our heat pipes with metallic casing, which contact directly with the heat-generating surface instead of water block usage. A reservoir is not necessary anymore, as we work only with gaseous state of a fluid. As the result, the system becomes simpler and could even be used in laptops. However, it is still could be the need in connecting a heat exchanger or a pump outside the laptop, depending on the exact model design.

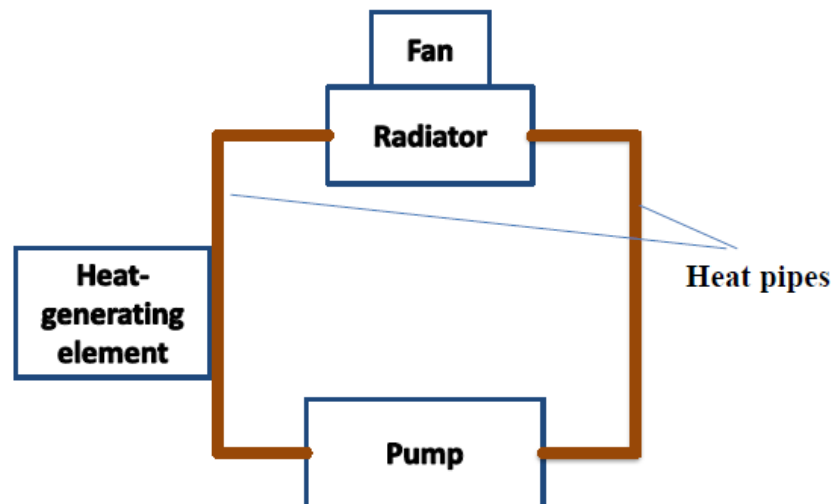


Figure 5. Proposed cooling system.

Concluding this, the cooling system we proposed is not such complex and massive as usual water cooling systems and could be even build-in a laptop, being at the same time

more effective than existing heat pipes alone. However, some difficult issues should be solved in future:

- proper model of a heat exchanger to cool down the refrigerant below the ambient temperature, as the existing solutions does not suit;
- careful design of the whole system in order to avoid leakage and condensation in the places of connection as well as in the transmitter and receiver installation spots;
- appropriate dimensions of the system in order to utilize it in laptops, not only personal computers or data servers, where space is not very limited.

In order to use this system with information exchange function, the pipe pieces should be straight and have point-to-point transmitters at the end of these pieces. The functionality of a pipe piece is presents in the section 2.4. Before that, the channel communications frequency should be chosen in order to understand characteristics of a waveguide.

2.3 Channel communications frequency

Channel communications for the chip-to-chip interconnections via waveguides should have wide bandwidth in order to provide reasonable capacity. Typical for the present communications MHz frequencies are hardly suitable for the proposed application as it offers only tens or, in the best case, hundreds of Mbps due to very limited available bandwidth. The other way is the use of millimeter (mm) waves. Mm-waves lay in the frequency range 30 – 100 GHz (10 – 3 mm, correspondingly) and utilizes for point-to-point communications and intersatellite links. However, only a few sub-bands are available for communications: 38.6 – 40 GHz, 57 – 64 GHz, 71 – 76 GHz, 81 – 86 GHz and 92-95 GHz. The sub-band 38.6 – 40 GHz is used for high-speed microwave data links. The 71-76, 81-86 and 92–95 GHz sub-bands provided for point-to-point high bandwidth communications do not have effects of oxygen absorption; however, transmitting license in the United States is required for them. Data rates at these frequencies could achieve up to 10 Gbps, except the 92 – 95 GHz band where a 100 MHz range has been reserved for space-borne radios limiting a transmission rate of under a few Gbps. The promising communications band is 57 – 64 GHz as it has the highest available bandwidth of 7 GHz wide. However, at these frequencies signal is severely attenuated by the oxygen molecules limiting total available bandwidth. Absorption loss is maximum at 60 GHz. Still, transfer rate is up to 7 Gbps at the distances up to 10 m (standardized by IEEE 802.11ad). All sub-bands except 57 – 64 GHz band are licensed in the United States. Unlicensed type of communications is preferable for the proposed application. Nevertheless, such data rates being much better than in any system below 5 GHz is not sufficient for the channel capacity of the proposed system and, moreover, mm-wave range is essentially undeveloped and available for use in a broad range of new products and services.

The next available frequencies are THz range between 100 GHz – 10 THz and fiber optics in the range approximately 180 – 330 THz. Optical frequencies allow having extremely high capacity. However, they have a number of drawbacks for our particular application:

- require special equipment not appropriate for the proposed waveguides;
- not easy to generate the signal;
- high signal attenuation (in the open space communications);
- difficult to combine with the cooling system.

The best choice for the channel communications is the THz frequency range as it allows having enough high data rates (up to a few Tbps) due to extremely wide bandwidth (almost 10 THz) and is applicable in the proposed waveguides. Besides, THz communications is not regulated yet and, thus, band licensing is not required.

2.4 System model

For the system model we analyze a straight piece of a heat pipe of length l and diameter d with refrigerant inside. 3D model, shown in Figure 6, is designed (and further analyzed) in COMSOL Multiphysics. The terminator at the entrance injects refrigerant at the constant flow rate r_l and constant temperature t_l . Flowing through the channel, the refrigerant absorbs the heat from the environment via metallic walls having a certain thermal conductivity. Then the heated refrigerant is taken out at the end of a pipe.

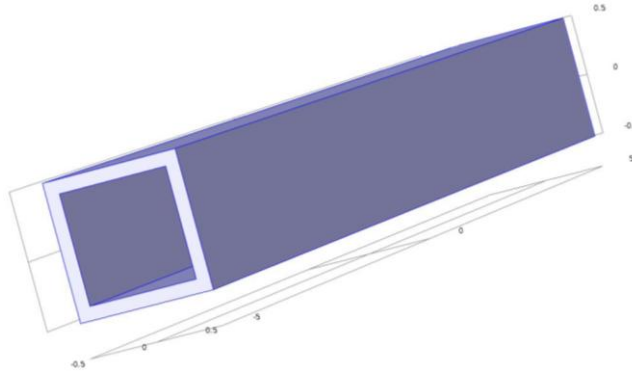


Figure 6. 3D model of a piece of a heat pipe.

The terminators at the both ends also have transmitter and receiver of THz radiation (see Figure 7) responsible for communications between components of interest. The problem of creating THz emitters have been extensively addressed in the literature with a number of prototypes available. The most common principle is to use laser to irradiate a certain semiconductors. The size of these antennas could be built small allowing integrating them into future components. *Optimal performance of the system and the choice of particular sub-band in 0.1-10 THz range of frequencies depend on the choice of system components. To provide description of the system we have to specify: (i) the type of*

refrigerant, (ii) the type of medium used to create a pipe's casing. Since the choice of these materials strongly depends on the properties of signal propagation at the THz frequencies, the next chapter provides the necessary description of them.

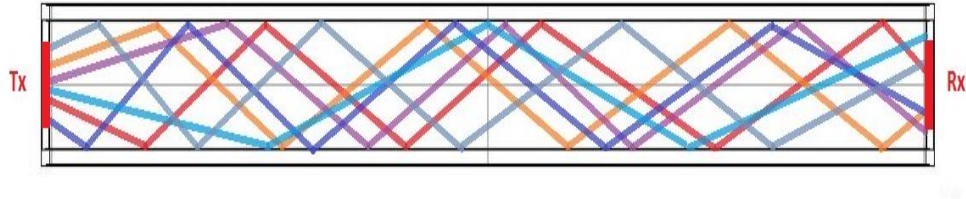


Figure 7. Conceptual illustration of signal propagation inside a heat pipe.

3. THEORETICAL BACKGROUND OF TERAHERTZ RADIATION

3.1 General description

The terahertz range refers to electromagnetic waves with frequencies between 100 GHz and 10 THz and wavelengths between 3 mm and 30 μm , correspondingly. It is also known as the submillimeter band due to millimeter and shorter wavelength.

The electromagnetic spectrum is shown in Figure 8. The sources for the lower frequencies, including radio-waves and microwaves, are based on electric generation controlled by the conventional transport of electrons. At these frequencies, most dielectric materials are transparent what makes possible radio reception and cellular telephony. Imaging applications such as radar has the resolution on the order of the wavelength and is usually limited to a few centimeters.

Higher frequencies in the spectrum lay in the optical range, including infrared radiation, visible light, and ultraviolet radiation. In this frequency range the light is generated by quantum transitions mostly by using lasers, which can form very high intensities. EM radiation in this range propagates in free space according to the geometrical optics laws. Thus, many materials are opaque, and optical radiation is strongly scattered by dust, fog, or grains in heterogeneous materials.

THz radiation falls in between these two regions (microwave and infrared radiation). Since it represents the transition between the electric and photonic sources, EM radiation in the THz range can be generated both ways. However, typical devices for generation and modulation used for radio- and microwaves are not suitable for THz waves and, thus, new devices and techniques are need to be developed. The development of modern microfabrication techniques, as well as the capability to produce structures on the order of a few tens of micrometers in electronic and hybrid optoelectronic devices, is important for the development of THz sources and receivers [6].

Similarly to infrared and microwave radiation, THz waves travel in a line of sight. Opposite to the X-rays, THz radiation is non-ionizing and similarly to microwaves it can penetrate a wide variety of non-conducting materials. THz radiation is transparent for paper, cardboard, wood, clothing, plastic and ceramics, reflects from metals and cannot penetrate water. The penetration depth is less than that of microwave radiation and depends on the particular frequency. Such fact also allows building a few micrometer thin mirrors for the THz signal generation in time-domain spectroscopy.

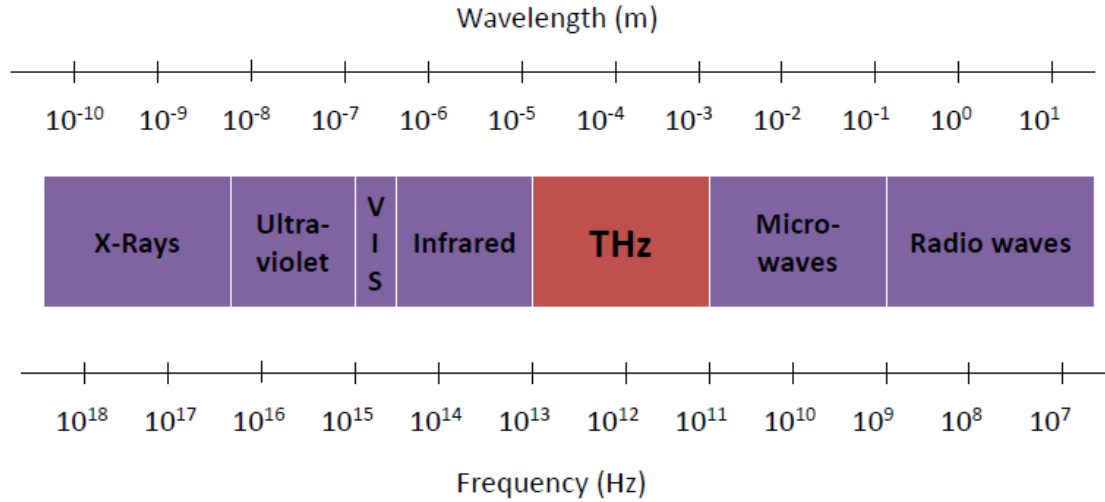


Figure 8. THz band in the EM spectrum.

Finally, particle scattering causes strong attenuation increased when the particle size is near to the wavelength of EM radiation. This fact explains THz propagation through the dust. The energy of a THz photon is on the order of a few milli-electronvolts and is equivalent to temperatures below 70 K. Therefore, semiconductor-based detectors should be cryogenically cooled. Thermal radiation which generates a lot of background noise is the main source for THz radiation [6].

3.2 Signal propagation in the THz band

Nowadays, the THz band, 0.1-10THz, is already used for various purposes including imaging, spectroscopy, remote gas sensing, etc. First studies of THz band for wireless communications appeared in the beginning of 2000s showing that using the directional transmission, the received signal-to-noise ratio (SNR) could be very high. Nevertheless, there was only slight progress in THz communications so far. The reasons for slow adoption are due to complex way to generate THz waves and special propagation properties at these frequencies.

The major shortcoming of communications at THz frequencies is the strong absorption through the atmosphere caused by water vapor molecules. Water molecules absorb THz radiation due to molecular rotations and vibrations. These rotation and vibration positions imply absorption lines where the radiation is absorbed more (Figure 9). Therefore, the important issue for the proposed application is to design the system such a way in order to minimize the effect of absorption.

Recently, researchers started to support the use of THz band for ultra-broadband board-to-board networking. It was stimulated by the recent progress in materials science and associated research on graphene THz antennas. However, the application of THz band communications was considered to be limited to extremely small distances on the order

of few millimetres. The reason is that, to achieve high data rates (e.g. few Tbps) the authors usually suggest to use the entire band, 0.1-10THz. To understand principal limitations of this approach consider the link budget:

$$P_{Rx}(f, d) = P_{Tx}(f, d) - L_p(f, d) - L_A(f, d) \quad (1)$$

where P_{Rx} is the power spectral density (p.s.d.) of the received signal, P_{Tx} is the p.s.d. of the transmitted signal, $L_A(f, d)$ is the loss caused by molecules absorbing THz radiation when a wave travels in the medium, $L_p(f, d)$ is the free-space propagation loss. In addition to the losses in (1), the received signal at the receiver is affected by the molecular absorption noise as molecules re-emit a part of the absorbed energy back to the channel.

3.2.1 Molecular absorption

As it was said above, molecular absorption loss $L_A(f, d)$ is caused by vibrating and rotating modes of molecules. Such molecular absorption occurs when the resonant frequency of the internal vibrational mode of a molecule matches with the EM wave frequency of a signal. At these frequencies molecule absorbs EM radiation and converts it into kinetic energy. Bond structure, spatial orientation and other physical properties of the molecule define its ability, which is determined by the absorption coefficients, to absorb EM energy. Molecules of water and water vapor are the main source of absorption in standard environment.

Absorption loss is determined as follows:

$$L_A(f, d) = 1/\tau(f, d), \quad (2)$$

where f is the operating frequency, d is the distance between the transmitter and the receiver and τ is the transmittance of the medium [10]. Transmittance of the medium can be modeled as exponential function following the Beer-Lambert law:

$$\tau(f, d) = e^{-K(f)d} = e^{-\sum_{G,I} k_{G,I}(f)d}, \quad (3)$$

where $K(f)$ is the overall absorption coefficient. It is calculated by summing up the individual absorption coefficients, $k_{G,I}$, of molecules of a single isotopologue I of gas G . Individual absorption coefficients are estimated as:

$$k_{G,I}(f) = Q_{G,I} \sigma_{G,I}(f) p T_0 / p_0 T, \quad (4)$$

where p_0 is the standard pressure and T_0 is the standard temperature, p and T are the pressure and temperature of the medium, respectively, $Q_{G,I}$ is the volume density of molecules, and $\sigma_{G,I}$ is the cross-section absorption [4]. The volume density and the cross-section absorption are determined as:

$$Q_{G,I} = p N_A Q_{G,i} / RT, \quad (5)$$

$$\sigma_{G,I}(f) = S_{G,I}G_{G,I}(f), \quad (6)$$

where N_A is the Avogadro constant equal to $6.02 \cdot 10^{23} \text{ mol}^{-1}$, R is the gas constant equal to $8.31 \text{ J/K}\cdot\text{mol}$, $S_{G,I}$ is the linear absorption intensity, and $G_{G,I}$ is the form of the spectral component. Parameters $S_{G,I}$ and $G_{G,I}$ are presented in [7] and analytically estimated in [10]. If special pressure-temperature conditions are pointed, additional corrections for $G_{G,I}$ are required. First, the resonant frequency of each isotopologue I should be defined. Besides, absorption increases when pressure increases jointly with linear increasing frequency. However, this affect is almost negligible for $L_A(f, d)$ with the common pressure variations.

The important feature of the molecular absorption is that it is a highly frequency selective process. Due to molecules peculiarities implying its physical properties, the absorption could be negligible at some frequencies and very high at other frequencies resulting on the radiation capability in the extremely small communication range. Addressing the equation (4), absorption coefficient $K(f)$ does not depend on distance d , however, the absorption loss, $L_A(f, d)$, does depend on the distance, via (2) and (3). Thus, in order to provide the minimum absorption loss with long distance, $K(f)$ should be at minimum. Consequently, the medium of the propagated signal should have as less absorption lines in the considered band, $0.1 - 10 \text{ THz}$, as possible in order to provide the best communications characteristics.

3.2.2 Free Space Propagation

The next important parameter affecting the received signal is the free-space propagation loss which is determined as:

$$L_p(f, d) = (4\pi fd/c_0)^2, \quad (7)$$

where f is the operating frequency, d is the distance between the transmitter and the receiver, and c_0 is the speed-of-light in the certain medium (for open air $c_0 \approx 3 \cdot 10^8 \text{ m/s}$). According to this equation, when the frequency increases it results in quadratic increase of the free-space propagation loss. If absorption coefficients in the particular medium are minimum and, consequently, absorption loss is not the dominating factor in the path loss, then the free-space propagation loss becomes the main factor limiting the coverage area of the transmitter. Thus, in order to minimize the free-space propagation loss, one should use lower operating frequencies or lower transmission distances.

Figure 9 shows the overall loss including molecular absorption and free-space propagation loss in the air for distances $d = 0.1 \text{ m}$ and $d = 1 \text{ m}$, with 1.8 % of vapor and standard temperature-pressure conditions ($T = 273 \text{ K}$, $p = 760 \text{ mmHg}$). Figure demonstrates that, the main limiting factor for the medium with water molecules is molecular absorption loss. However, medium with no absorption would allow to utilize the whole frequency

band leading to ultra-wide band communications where the only free-space propagation loss presents. Alternatively, the medium with minimum clearly distinguished absorption lines could also be applicable; though, in this case, the frequency band will be divided into sub-bands allowing to have lower data transfer rates.

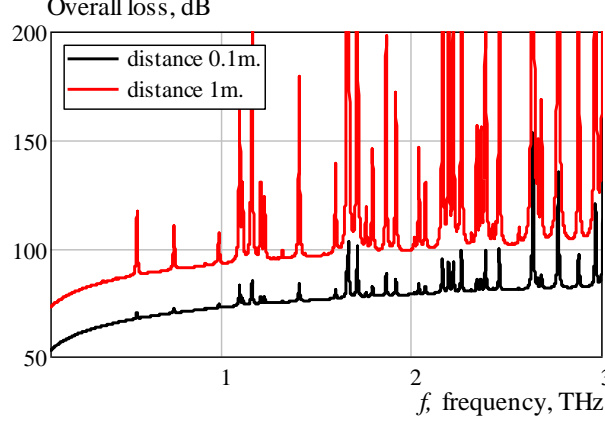


Figure 9. Overall loss (propagation and absorption) in the 0.1-3 THz band.

3.2.3 Molecular absorption noise

As it was said, molecules absorb EM radiation and convert part of it into kinetic energy. At the same time, part of this absorbed energy is re-emitted in the channel, generating the so-called molecular absorption noise. The p.s.d. $P_N(f, d)$ of molecular absorption noise can be written as:

$$P_N(f, d) = k_B [N_M(f, d) + N_B], \quad (8)$$

where k_B is the Boltzmann constant, $N_M(f, d)$ is the equivalent molecular absorption noise temperature expressed via transmittance of the medium, $\tau(f, d)$, as $N_M(f, d) = T [1 - \tau(f, d)]$ and having maximum at approximately -204dB/Hz, N_B is the thermal noise that is constant for 0.1-10THz range [4].

Figure 10 shows power spectral density of molecular absorption noise in the air for distances $d = 0.1$ m and $d = 1$ m with 1.8 % of vapor and standard temperature-pressure conditions ($T = 273$ K, $p = 760$ mmHg). One can observe that molecular absorption noise has the similar behavior with the absorption loss as it has significantly lower values at some frequencies than at the others. Having maximum of the transmittance of the medium at approximately -204dB/Hz could result into very high noise power when the system applies a very large channel bandwidth.

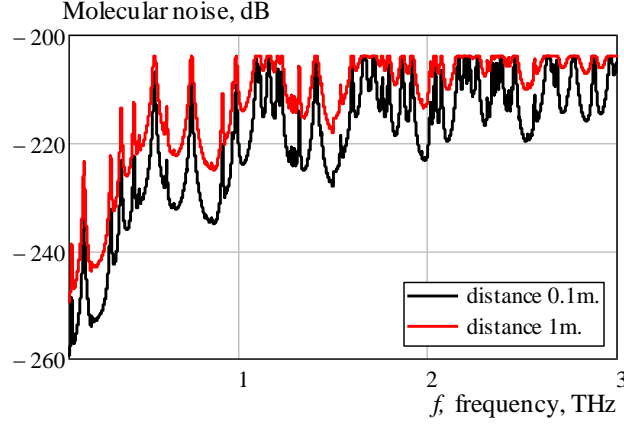


Figure 10. *Molecular noise in the 0.1-3 THz band.*

Concluding the above-mentioned properties, the overall losses and molecular noise shown in Figure 9 and Figure 10 highlight that the use of the whole range 0.1-10 THz in the standard air environment can only provide communications at extremely small distances (up to few millimeters) as the signal gets quickly absorbed by water vapor. While the molecular absorption and noise play important roles when either the whole THz band (0.1-10THz) is used for communications or low transmission energy is of interest (e.g., less than $10e^{-18}W$) their effects becomes negligible in the air channel. Thus, in order to avoid significant effects of molecular absorption and noise and get the best parameters at the receiver, the medium of a channel should have no absorption or have as less as possible.

3.3 Communications characteristics

THz communication means effective data rates exceeding 1 Tbps (typically on an optical carrier). Although eventually greater bandwidths can be obtained at optical wavelengths with point-to-point optical communications, communications at the THz frequency range is more attractive due to a number of reasons including the availability of the frequency band and the unlicensed communications bandwidth [6].

3.3.1 Capacity

Assuming that the transmitted signal and the total noise are Gaussian, the capacity C can be determined using the classic Shannon approach:

$$C(d) = \int_{B(d)} \log_2 \left(1 + \frac{P_{Tx}}{L_p(f,d)L_A(f,d)N_M(f,d)} \right) df, \quad (9)$$

where B is the channel bandwidth dependent on distance, P_{Tx} is the p.s.d. of the transmitted signal, $L_p(f,d)$ is the free-space propagation loss, $L_A(f,d)$ is the molecular absorption loss, and $N_M(f,d)$ is the molecular absorption noise.

Figure 11 illustrates the channel capacity for the 0.1-0.54 THz band as a function of distance for three different transmission pulse energies at a standard conditions ($T=273$ K, $p=760$ mmHg, 1.8 % of vapor molecules) [4]. The 0.1-0.54 THz band is taken due to negligible absorption in the air. Observing the data, we can notice that even using the bandwidth of 440 GHz we can get extremely high capacity of few Tbps at distances up to few cm. Higher pulse energy provides higher capacity.

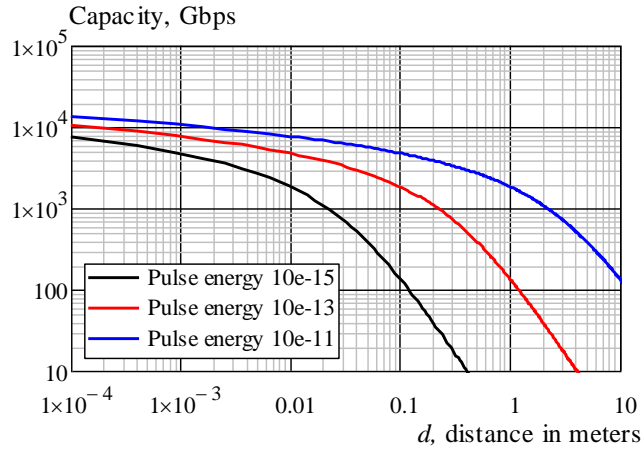


Figure 11. Capacity for 0.1-0.54THz channel.

3.3.2 Signal-to-Noise Ratio

Besides capacity, we should also take into account Signal-to-Noise Ratio (SNR) affecting the achievable data rate. SNR presented on Figure 12 is a function of distance for three different transmission pulse energies at a standard conditions ($T=273$ K, $p=760$ mmHg, 1.8 % of vapor molecules). The same 0.1-0.54 THz channel is considered [4]. Figure shows that distances from one up to few meters are reachable applying $\text{SNR} = 10$ dB as the lower limit.

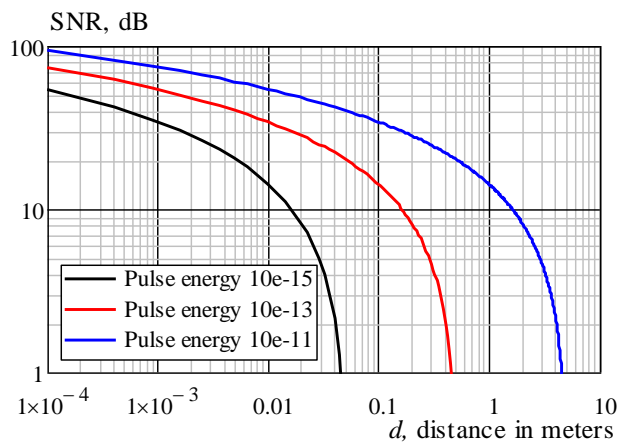


Figure 12. SNR for 0.1-0.54THz channel.

Concluding the above-mentioned communication characteristics, one can achieve distance of up to two meters with SNR at least 10dB and the corresponding capacity of more than 1Tbps using $10e^{-11}$ W transmission pulse energy. At slightly smaller distances even higher capacity is achievable, e.g. using $10e^{-11}$ W we may provide 6Tbps with SNR 35dB at 0.1m. Such short distances are perfectly suitable for the proposed architecture. Thus, the selected THz frequency band may indeed be of great use for communications at short distances potentially providing extremely high data rate in almost noise-free environment. The values of capacity and SNR reported above could be increased even further with the use of directional antennas. The main issues ahead are the choice of the appropriate medium with no absorption for signal propagation and the choice of casing material for a waveguide in order to provide directional transmission. They are considered in the next chapter.

4. CHOICE OF MATERIAL

4.1 Cooling medium

Due to transmission on the THz band, we should consider not only reflections and diffractions of the propagated signal, but also its absorption. Thus, the cooling medium should not have absorption lines or have it as less as possible. Water, air or special refrigerants can be utilized as the cooling substance in the heat pipe. However, absorption of the medium should be taken into account for the information transmission inside the pipe. In order to have not significantly attenuated signal, the medium should have as less absorption as possible. Water has strong absorption in the terahertz frequency range, as well as the air with water vapor. This is the case with water and water vapor in the whole 0.1 – 10 THz preventing from their usage as coolant inside the heat pipe. However, there are a number of special refrigerants that can be utilized in heat pipes. For our purpose, the refrigerants should satisfy the two constraints:

- 1) to have as few absorption lines in 0.1 – 10 THz range as possible;
- 2) to have temperature of phase transition between liquid and gaseous states not extremely low.

Absorption coefficients for water, air of different humidity (dry air of 0.76 g/m³ absolute humidity and humid air of 22.86 g/m³ absolute humidity [18]) and refrigerant ammonia are shown at the standard temperature and pressure conditions ($T = 273\text{K}$, $p = 760\text{ mmHg}$) on Figures 13 – 16 [7]. It can be seen that water has exceptionally strong absorption in the full considered THz band. Air has a lot absorption lines as well due to the presence of water molecules. One can also observe that dry air and humid air have approximately the same absorption spectra, which are distinguished only by the value of absorption coefficients. This is again mostly due to the presence of water molecules, contents of which is sufficiently less in dry air. Though the level of absorption in air is significantly less than the level of water, we still cannot use air for the signal propagation in the THz range.

On the other hand, ammonia has clearly distinguished absorption lines which can be avoided by proper selection of the frequency band. Therefore, refrigerants are more suitable for the usage as medium inside the heat pipe.

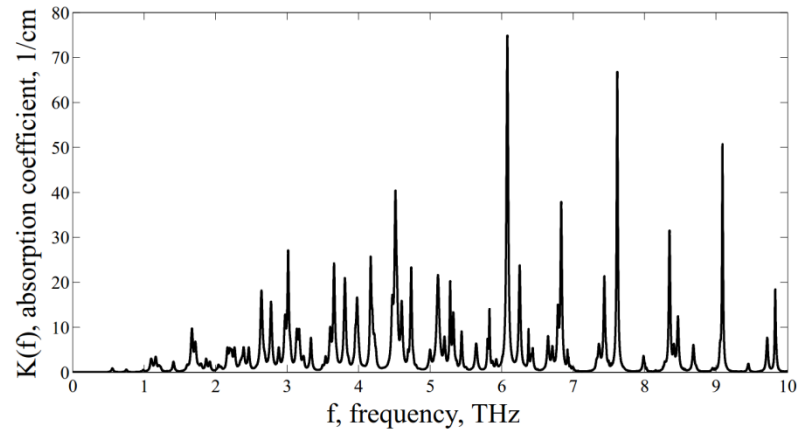


Figure 13. *Absorption coefficients for water vs. frequency.*

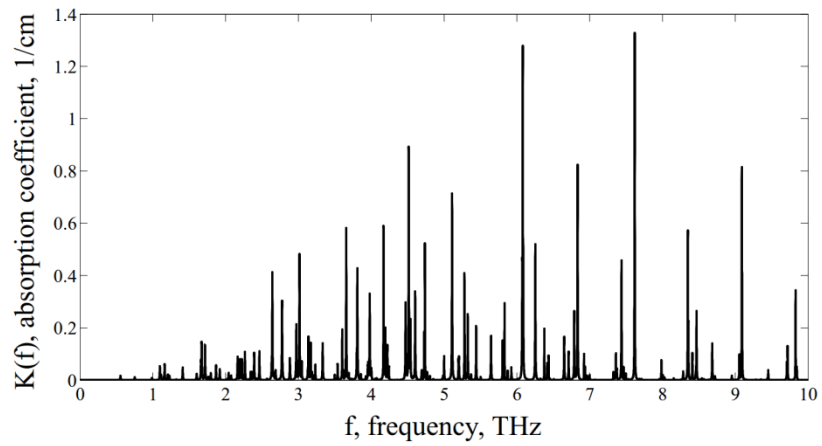


Figure 14. *Absorption coefficients for dry air vs. frequency.*

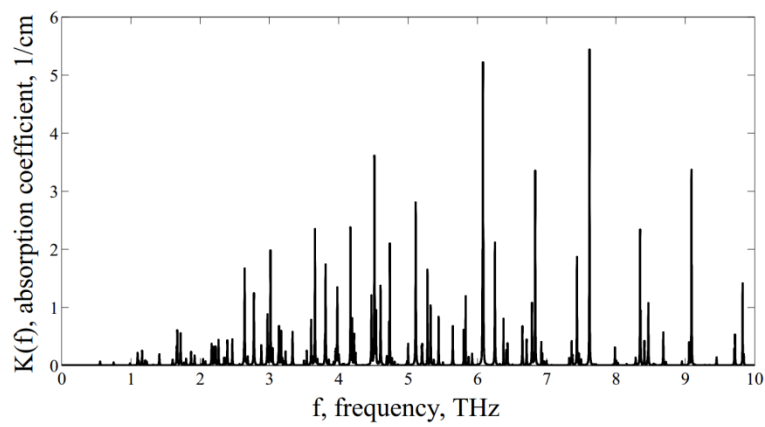


Figure 15. *Absorption coefficients for humid air vs. frequency.*

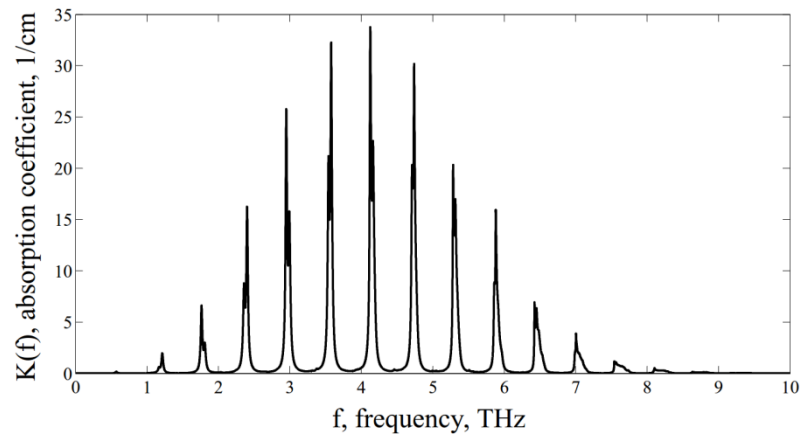


Figure 16. Absorption coefficients for ammonia vs. frequency.

There are plenty of refrigerants utilized nowadays for different purposes. Not all of them can be freely used due to harmful effect on the environment. We considered the most popular refrigerants. Relevant physical properties of mostly used refrigerants are summarized in Table 1. These refrigerants were selected taking into account the above-mentioned constraints - phase transition temperature and absorption in the THz band. The considered properties include the presence of absorption lines in 0.1–10 THz band [7], real part of refractive index [17], [26], boiling point in Celsius [17], [20] and the effect on environment expressed using ODP and GWP indices [5].

Table 1. Parameters of the refrigerants.

Refrigerant	Absorption in the frequency range 0.1 – 10 THz	Refractive index, real $n(f)$, (gas state)	Boiling point	Impact on the environment (ODP, GWP)
Isobutane C ₄ H ₁₀ (R-600a)	No absorption lines	1.3518	-11.7 °C	ODP=0 – negligible, GWP=3 – very low
Ammonia NH ₃ (R-717)	No significant absorption below 1 THz	1.3327	-33.3 °C	ODP=0 – negligible, GWP=0 – negligible
Propane C ₃ H ₈ (R-290a)	No absorption lines above 0.3 THz	1.2898	-42.1 °C	ODP=0 – negligible, GWP=3.3 – very low
Tetrafluoroethane CH ₂ FCF ₃ (R-134a, HFC-134a)	No absorption lines	1.225	-26.3 °C	ODP=0 – negligible, GWP=1430 - high
Chlorodifluoromethane CHClF ₂ (R-22, HCFC-22)	No absorption lines	1.256	-40.8 °C	ODP=0.055 – significant, GWP=1810 – high

The first considered parameter is absorption. Concerning to the absorption lines, propane (C₃H₈, R-290a) has limitation for the usage in the range below 0.3 THz due to significant amount of absorption lines. However, it is also suitable for frequencies above 0.3 THz. Ammonia (NH₃, R-717) has no significant absorption lines below 1 THz but there are few above, as seen from the Figure 16. There are no absorption lines for

isobutane (*R-600a*), tetrafluoroethane (*R-134a*, *HFC-134a*) and chlorodifluoromethane (*R-22*, *HCFC-22*) and they could be utilized for communications in the whole band.

For absorbing media, index of refraction is of importance as it influences to the signal propagation in time-variant electromagnetic fields. In the terahertz range electromagnetic properties of the signal radiation are frequency-depended and can be expressed through the complex index of refraction:

$$\tilde{n}(f) = n(f) + ik(f), \quad (10)$$

where real part, $n(f)$, indicates the phase velocity or refraction of light in the medium and imaginary part, $k(f)$, describes attenuation due to absorption loss. Imaginary part $k(f)$ is also called extinction coefficient and proportionally to the absorption coefficients, $K(f)$, introduced previously, through the relationship:

$$k(f) = K(f)c/4\pi f, \quad (11)$$

where c is the speed of light.

Real part of the index of refraction, $n(f)$, (see Table 1) does not drastically vary for different refrigerants, therefore it does not have a high impact to the final choice of the medium. Imaginary part, $k(f)$, is determined by the absorption coefficients and, hence, there is no imaginary part of the index of refraction if there is no absorption. Otherwise, we should use absorption coefficients for imaginary part.

The next important parameter is the boiling point. Boiling point of the refrigerant is the temperature point of phase transition from the liquid to gaseous state. Taking into account the discussion above, the boiling point is the major factor affecting the final choice of refrigerant. Higher boiling temperature is more preferable as the heat pipe is working only with gaseous state and, hence, there is no need in the powerful cooling system to cool the refrigerant. Data is given at the atmospheric pressure. As one can observe, isobutane has the highest temperature of boiling point. Ammonia and tetrafluoroethane are also suitable comparing with propane and chlorodifluoromethane, which have too low boiling temperature for our purpose.

Finally, when dealing with refrigerants, we always should remember about their effect on the environment. Impact on the environment is considered from the point of view of the Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), which are recognized by the Montreal Protocol. ODP is a relative value that indicates the potential of a chemical compound to destroy the ozone layer comparing with the potential of chlorofluorocarbon-11 (CFC-11) which is assigned to the reference value 1.0. Thus, for example, a chemical with $ODP = 2$ is twice more harmful than CFC-11. ODP is usually used in combination with GWP. GWP is a measure of the heat trapped in the atmosphere by a greenhouse gas. Specifically, it is a relative measure of how much energy the

emissions of a gas will absorb over a given period of time relative to the emissions of the similar mass of carbon dioxide. The larger the GWP, the more a given gas warms the atmosphere compared to carbon dioxide. GWP is calculated over a specific time interval, usually 20, 100 or 500 years. GWP of carbon dioxide is standardized to the reference value 1. These parameters, ODP and GWP, should be negligible or low for the safe use otherwise the usage is limited. ODP is zero for all considered media except for chlorodifluoromethane, which has significantly high ODP = 0.55. The use of this refrigerant is already sufficiently limited and it is planned to exclude its usage at all by 2020 year. GWP is not that important as ODP, however, tetrafluoroethane and chlorodifluoromethane have quite high values 1430 and 1810 correspondingly what prevents their widespread use according to the Montreal protocol. The other first three media have very low GWP. Hence, isobutane R-600a, ammonia R-717 and propane R-290a are the most friendly environmentally refrigerants.

Concluding absorption, boiling point and impact on the environment, isobutane is the most suitable refrigerant for the use in the frequency range 0.1 – 10 THz as it satisfies all criteria in the best way. Other refrigerants in Table 1 are listed in the order of preference of their parameters.

4.2 Casing material

We have two constraints on the choice of casing material:

- it should absorb as less THz radiation as possible;
- it should conduct the heat.

In addition, we assume that inner surface of a heat pipe is very well polished in order that no diffraction and scattering occurs with only reflection influencing the transmission.

Metals and polymers can serve for the casing of the heat pipe. However, polymers are transparent and almost dispersionless at THz frequencies and, thus, the transmitted signal inside the pipe will be dissipated out of pipe instead of to be highly directional. To obtain a directional transmission and to force the pipe to serve as a waveguide, metals should be utilized as a casing material of the heat pipe due to their high reflectivity. The reflectivity of a metal surface is near unity in the considered THz region due to high electrical conductivity. Therefore, polished metal surfaces or metal coating mirrors are commonly used as THz reflectors [16], [19]. The most commonly used metals for such purpose are gold, silver, copper and aluminium. The basic properties of these metals in the 0.1–10THz band are summarized in Table 2. These parameters include electrical conductivity, σ ; skin (penetration) depth, δ , and thermal conductivity, κ . The electrical conductivity influences the reflectivity determining how well the signal is reflected from the inner surface of a pipe. Penetration depth determines the minimum allowable thick-

ness of the material layer affecting the amount of radiation remaining inside. Finally, thermal conductivity expresses the ability of a material to transfer the heat. First two parameters influence on the information transmission while the latter one affects the cooling efficiency.

Table 2. *Parameters of common metals.*

Metal / property	Electrical conductivity (σ), $10^6 \text{ S}\cdot\text{m}^{-1}$	Penetration depth (δ) at 1 THz, nm	Thermal conductivity (κ), $\text{W}/(\text{m}\cdot\text{K})$
Au	45.2	74.9	308
Ag	63.0	63.4	407
Cu	59.6	65.2	384
Al	37.8	81.9	209

The THz region is usually out of optical phonon resonances. Still, the low-energy spectrum tail is a major source of absorption at these frequencies. In general, the dielectric response of vibrational modes decays as frequency decreases in the THz region [16]. The optical properties at the THz range are well described by the Drude model of electrical conduction in the following form:

$$\sigma(\omega) = \sigma_0 / (1 - i\omega\tau), \quad (12)$$

where $\sigma(\omega)$ is electrical conductivity, ω is the angular frequency, τ is relaxation time and σ_0 is static conductivity.

Due to the fact that the relaxation times of the abovementioned metals are on the order of $10\text{e-}14\text{s}$, $\omega\tau$ is much less than 1. Therefore, the Drude model can be simplified as $\sigma(\omega) \approx \sigma_0$ [16], [2] showing that the electrical conductivity σ is independent of frequency ω . Electrical conductivity σ shown in the Table 1 does not drastically vary for the common metals.

Reflectivity of metals at normal incidence has the form:

$$R(\omega) = |(\tilde{n}(\omega) - 1)/(\tilde{n}(\omega) + 1)|^2, \quad (13)$$

where $\tilde{n}(\omega) = \sqrt{\mu_r(\omega)\epsilon_r(\omega)}$ is the refractive index, depends on relative permittivity $\epsilon_r(\omega)$ and relative permeability $\mu_r(\omega)$ of the given material. Since $\mu_r(\omega)$ is approximately one for considered metals and independent of the frequency, formula for the refractive index could be further simplified as: $\tilde{n}(\omega) = \sqrt{\epsilon_r(\omega)}$.

The relative permittivity or dielectric constant $\epsilon_r(\omega)$ is given by:

$$\epsilon_r(\omega) = \epsilon_b + i\sigma(\omega)/\epsilon_0\omega \approx \sigma_0/\epsilon_0\omega, \quad (14)$$

where ε_b is the contribution from bound electrons [16], ε_0 is the permittivity of vacuum. In the THz range $\sigma_0/\varepsilon_0(\omega) \gg \varepsilon_b$, and thus the reflectivity can be expressed as:

$$R(\omega) \cong 1 - \sqrt{8\varepsilon_0\omega/\sigma_0}. \quad (15)$$

Reflectivity of the common metals is shown on the Figure 17. The data is calculated using equation (15). One can observe that reflectivity insignificantly decays from unity with increasing frequency and nearly equal for all these metals. However, silver and copper have the highest values of electrical conductivity and, respectively, reflectivity. Thus, considering the reflectivity, silver and copper are the best metals for our application.

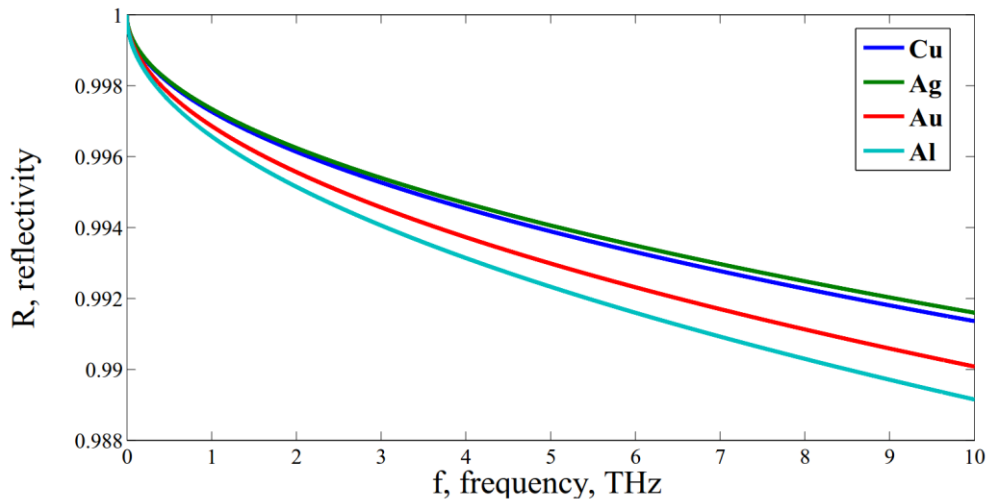


Figure 17. Reflectivity vs. frequency for Cu, Ag, Au and Al.

The thickness of a metal or metal coating is also should be taken into account. In order to achieve maximum reflectivity for a given metal, the thickness of the metal layer must be at least two penetration depths, δ at the frequency of the incident beam [19]. Penetration depth or skin depth is the attenuation length of exponentially decaying electromagnetic field when the wave is incident on a conductor and expressed as:

$$\delta = \sqrt{2/\omega\mu\sigma}, \quad (16)$$

where $\mu = \mu_r\mu_0$ is the magnetic permeability, μ_0 is the permeability of vacuum.

The penetration depth is less than 100 nm at 1 THz for common metals (see Table 1). Thus, a few-micron-thick layer is sufficient for a reflector [16].

The next important parameter for selected materials is their thermal conductivity, k , which determines the ability of a medium to conduct the heat. Materials of high thermal conductivity are more preferable to be used in the heat sink applications as they allow taking out more heat. Thermal conductivity of common metals is shown in the Table 2.

As one can observe, the best heat conductors are silver and copper, while aluminium has the lowest value.

Concluding all the above mentioned requirements for the casing material, we can notice that the silver is the best choice. However, silver and gold are expensive metals as we are going to use only pure metal as the casing and not metal coating. Taking into account the price of metals, copper has also good parameters and is suitable for the mass-market, thus, it provides the best trade-off between cost and performance. Therefore, we use copper as the casing of the heat pipe in our calculations.

5. PERFORMANCE EVALUATION

5.1 Cooling performance

To evaluate the cooling performance, we consider the problem of cooling a general purpose processor. We assume a modern multi-core CPU, Intel Core i7- 5960x, the first 8-core processor with 22nm fabrication process using Haswell-E architecture with the die size of $17.6\text{mm} \times 20.2\text{mm}$. Dimensions of the pipe is chosen by considering the size of the processor as it should be able to compensate the generated heat energy while still maintaining the data transmission towards GPU or memory.

For cooling analysis we should examine a fluid flow in the channel. Two types of flow could be occur in the pipe depending on the velocity of the fluid: laminar flow or turbulent flow. Laminar flow is a type of fluid (liquid or gas) flow in which the fluid travels smoothly in parallel layers, without disruption between the layers or lateral mixing. Laminar flow occurs at low velocities. Turbulent flow is a flow regime characterized by irregular fluctuations and mixing. The flow has chaotic property changes including low momentum diffusion and rapid variation of pressure and flow velocity in space and time. The flow speed continuously changes in both magnitude and direction. Laminar flow is preferable for the channel as only in this regime we can find exact solutions of the fluid motion equations. Besides, turbulent effects may negatively affect the signal propagation inside the pipe. Laminar flow tends to occur at lower velocities, below a threshold at which it becomes turbulent. Parameter describing the flow regime is the Reynolds number R_e . A flow is in the laminar state if $R_e \leq 2000$. When the liquid with kinematic viscosity ν (m^2/s) flows in a cylindrical channel with a diameter D_H (m) at a rate of ϑ (m/s), the Reynolds number can be calculated as [3]:

$$R_e = \vartheta D_H / \nu. \quad (17)$$

The higher coolant flow rate leads to higher heat absorption. However, the flow rate cannot be increased infinitely as we need to ensure the flow to be laminar. Thus, we estimate the performance of the proposed system by considering the following issues:

- 1) defining the flow speed and its effect on the temperature,
- 2) temperature effect on the Reynolds number.

Parameters used in calculations are listed in Table 3, where TDP is a thermal design power, C_p is the heat capacity, ρ is the density and T is temperature in Celsius. Besides

the above mentioned processor Intel Core i7- 5960x, we also consider processors Intel Core i5 and Intel Core i3 to compare their parameters.

Table 3. Cooling performance evaluation parameters.

Parameter	Value [Unit]
TDP (Intel Core i3)	35 [W]
TDP (Intel Core i5)	65 [W]
TDP (Intel Core i7)	88 [W]
Processor Dimension	37.5 x 37.5 [mm ²]
Channel Width	0.8 [mm]
Channel Length	4 [cm]
C_p (Water)	4185.5 [J/kg K]
C_p (Ammonia)	2097.2 [J/kg K]
C_p (Isobutane)	1693 [J/kg K]
ρ (Water)	998.2071 [kg/m ³ K]
ρ (Ammonia)	0.860 [kg/m ³ K]
ρ (Isobutane)	2.8265 [kg/m ³ K]
T (Water)	20 [°C]
T (Ammonia)	-33.3 [°C]
T (Isobutane)	-11.7 [°C]

In order to compare cooling performance, we take water and two refrigerants:

1) ammonia (gas), 2) isobutane (gas).

Then we make calculations for all three processors. Both water and refrigerants (gaseous state) are based on the same principle of convective heat transfer and thus can be analyzed using the same approach. Assuming that the amount of required cooling is only on the contact surface of the core and contacting wall of the pipe is thin enough to be neglected, we can calculate the heat energy dissipated on the area as [24]:

$$q^* = E_{TDP} L_{ch} W_{ch} / A_{CPU}, \quad (18)$$

where E_{TDP} is the peak heat energy generated by a core, A_{CPU} is the surface area of a CPU, L_{ch} and W_{ch} are the contact length and width of the channel with the CPU surface. Then, we can obtain the mass flow rate of the coolant, whose specific heat capacity C_p is needed to absorb the dissipated heat energy with initial coolant temperature T_0 and equilibrium temperature T_E as:

$$m^* = q^* / C_p (T_E - T_0) = q^* / C_p \Delta T. \quad (19)$$

After that, we estimate the average speed of the coolant, ϑ , by:

$$\vartheta = m^* / \rho A_{ch}, \quad (20)$$

where ρ is the density in the channel and A_{ch} is the cross section area of a channel.

Finally, in order to ensure that the required flow speed is still laminar, the Reynolds number should be calculated by the equation 17.

The results are obtained by the simulation using MATLAB software. Simulation parameters presented in this chapter is based on the theoretical calculation using all physical properties of the corresponding elements and listed in Table 3.

The calculated results are presented in the Figures 18-21. Figure 18 shows relationship between the cooling process and the required flow speed and Figure 19 – between the cooling process and the Reynolds number for Intel Core i7. Figure 20 and Figure 21 demonstrate the results for Intel Core i3, i5 and i7 in order to compare cooling performance of the core.

Considering Figure 18 for Intel Core i7, it shows the relationship between the temperature of cooling process and the required flow speed of coolant in order to achieve corresponding equilibrium temperature. As it was said, the higher coolant flow speed leads to lower processor temperature due to higher heat absorption rate. We see that refrigerants are allowed to have higher flow rate than water what proves the effectiveness of refrigerants usage. Isobutane has lower flow speed than ammonia due to its chemical properties. Figure 19 shows the relationship between Reynolds number of continuous phase coolants and equilibrium temperature. Black line indicates the border between the laminar and the turbulent regimes. Considering the system with water coolant and the system with refrigerants, one can observe, that all coolants' curves are significantly lower than the black line. Therefore, the proposed refrigerants are as suitable to have laminar regime as water and, thus, do not have negative effects on the data transmission.

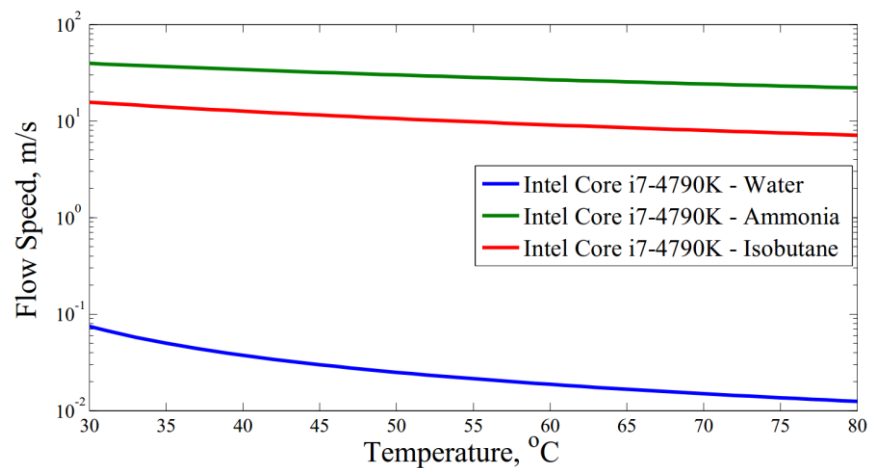


Figure 18. Speed of coolants vs. temperature for Intel Core i7.

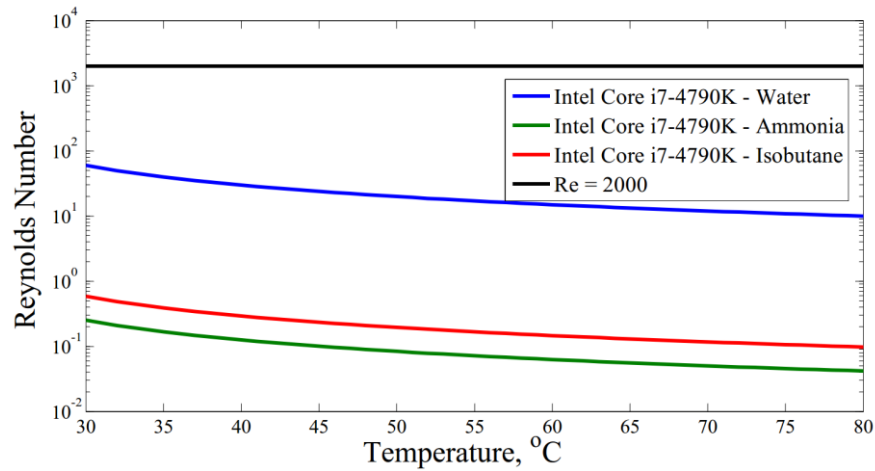


Figure 19. Reynolds number vs. temperature for Intel Core i7.

Addressing to Figure 20, we see that the Intel Core-i3 is allowed having lower flow speed than the Intel Core-i5 and the Intel Core-i7, while the Intel Core-i5 has lower flow speed than the Intel Core-i7. This is due to their TDP. As we see from the Table 3, TDP values are 33W, 65W and 88W for the Intel Core-i3, Intel Core-i5 and Intel Core-i7 correspondingly. Thus, in order to absorb more heat we need higher flow rate what we observe on the picture. Addressing to Figure 21 indicated the Reynolds number for the all cores, we also can observe that Core-i7 has higher Reynolds number than Core-i5 and Core-i3, what is a direct consequence of the TDP values. However, all cores have essentially lower Reynolds number than the borderline, that means, we can use both refrigerants for any core.

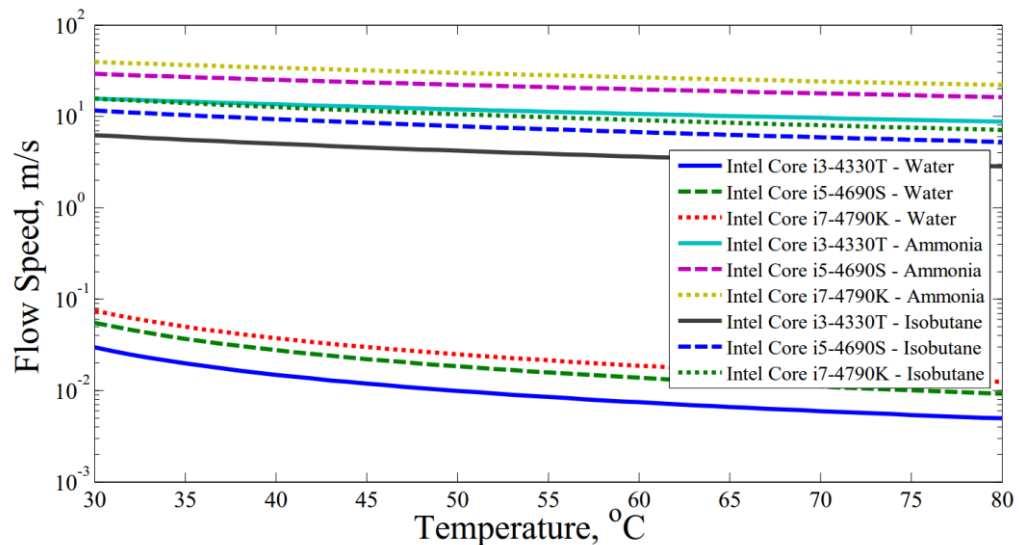


Figure 20. Speed of coolants vs. temperature for Intel Core i3, i5 and i7.

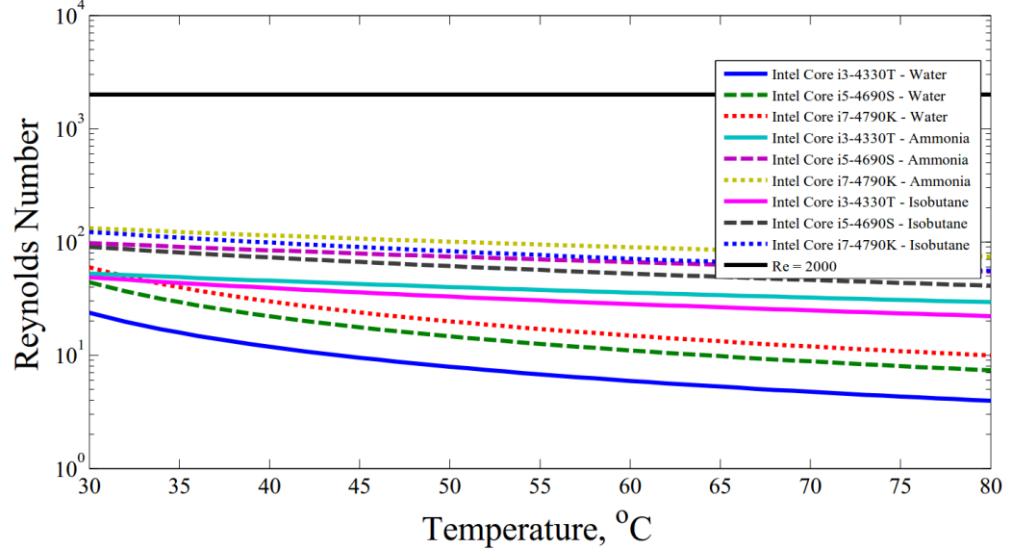


Figure 21. Reynolds number vs. temperature for Intel Core i3, i5 and i7.

5.2 Transmission performance.

To observe signal propagation in the terahertz range we utilized frequency-depended electromagnetic simulation in the RF-module of the software program COMSOL Multiphysics. This software utilizes two types of solvers: implicit and explicit. COMSOL mainly uses implicit solvers because they solve system of equations which enables to solve almost any task. Time explicit is not suitable for solving our task as we should know the time of the stable state of the system in advance. Therefore, frequency domain is chosen for the simulation.

RF-module solves Maxwell's equations using the finite element method with numerical-ly stable edge elements [21]. Finite element method is a numerical method of solving systems of partial differential equations. Domain under the solving is divided into a finite number of elements. Each element is represented by a set of element equations with coefficients equal in the neighbor nodes. Type of approximation function is randomly selected in each element. Values of the functions at the boundary of elements (nodes) provide the solution. Then, all sets of element equations are recombined into a global system of equations for the final calculation using the initial values to obtain a numerical result.

Initial Maxwell's equations are the following:

$$\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D} / \partial t, \quad (21)$$

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t, \quad (22)$$

$$\nabla \cdot \mathbf{D} = \rho, \quad (23)$$

$$\nabla \cdot \mathbf{B} = 0, \quad (24)$$

where \mathbf{E} is electric field intensity, \mathbf{D} is electric displacement or electric flux density, \mathbf{H} is magnetic field intensity, \mathbf{B} is magnetic flux density, \mathbf{J} is current density and ρ is electric charge density.

Under certain circumstances it can be helpful to formulate Maxwell's equations in terms of the electric scalar potential V and the magnetic vector potential \mathbf{A} :

$$\mathbf{B} = \nabla \times \mathbf{A}, \quad (25)$$

$$\mathbf{E} = -\nabla V - \partial \mathbf{A} / \partial t, \quad (26)$$

Then wave equation for the magnetic vector potential \mathbf{A} , which COMSOL solves, is the following:

$$\nabla \times \mu_r^{-1} (\nabla \times \mathbf{A}) + \frac{\mu_0 \sigma \partial \mathbf{A}}{\partial t} + \mu_0 \frac{\partial}{\partial t} \left(\varepsilon_0 \varepsilon_r \frac{\partial \mathbf{A}}{\partial t} \right) = 0, \quad (27)$$

where ε_r is relative permittivity or dielectric constant, μ_r is relative permeability, σ is electrical conductivity, ε_0 is the permittivity of a vacuum and μ_0 is the permeability of a vacuum.

Parameters ε, μ, σ depend on the material properties and temperature-pressure conditions. Besides, for time-variant electromagnetic fields in the THz range these parameters are frequency-dependent and should be expressed through the complex index of refraction as it was described in the section 4.1.

In Comsol Multiphysics we model the heat pipe using isobutane as the transmitting medium and the copper casing for the directional signal propagation. In order to measure the signal propagation and reflection inside the tube, the pipe should be considered as a waveguide (i.e., wavelength approaches to the cross-sectional dimensions of the waveguide) with periodic ports. The first port in the one end of the pipe serves for the excitation of the electromagnetic waves. On the other end of the heat pipe we set the point probe measured the value of the electric field. The cross-sectional size of the heat pipe is 1 mm and the same for the whole set of experiments where we used frequency sweeping between the range 0.1 – 0.6 THz. For higher frequencies, calculations become more complex and require more time for computing or better performance of the computer. In addition, for higher frequencies, the cross-sectional size of the pipe should also be changed according to frequency in order to satisfy the waveguide requirements.

Results for the intensity of the electric field on the receiver for isobutane, ammonia and water as media inside the pipe are shown in Figure 22 and Figure 23. Figure 22 repre-

sents results for 10 mm long of the pipe and Figure 23 demonstrated results for 5 mm long of the pipe. One can observe that there is a part up to 0.2 THz, where the field is very low for all media. It can be due to the fact that the cross-sectional size of the pipe is too small for these frequencies and signal does not reflect from walls, but just is attenuated due to distance. As it was said in the previous sections, reflection is important parameter because multiple reflections make the signal power level stronger at the receiver. For higher frequencies, the wavelength is smaller and suits to the pipe cross-sectional size. Thus, signal becomes to be reflected from the walls, amplifying the received power level. Making the pipe of the appropriate size for each frequency requires very high computational performance of a machine, but allows getting more correct results.

It can be seen on the Figure 22, that water has significant attenuation of the signal even in the low absorption region of the 0.1 – 0.6 THz sub-band. Thus, we can suppose that at the higher frequencies where water absorption is greater, signal would be attenuated totally. Ammonia also has attenuation at the first absorption line 0.55-0.6 THz but in the region 0.1 – 0.55 THz it has almost the same intensity of the electric field as isobutane. Isobutane does not have any absorption in the considered THz sub-band and intensity of the electric field of the signal increases insignificantly with increasing frequency. Oscillation shape of curves may be explained by multiple reflections and thus, signal at the receiver comes in phase or out of phase as well as the wave-shaping nature of the electric field excitation and propagation.

For the shorter pipe, 5 mm long, we were able to calculate the signal propagation up to 0.7 THz frequencies and results are shown on the Figure 23. Observing the data presented on the Figure 23, we notice that the length of the pipe does not drastically influence on the intensity of the signal at the receiver. Besides, results demonstrate that signal propagated in the ammonia after the absorption line at 0.55-0.6 THz amplifies again. It proves the effectiveness of the ammonia usage as the cooling medium in the case of careful frequency selection. Signal propagated on water has slight amplifying after significant absorption and isobutane still has increasing in the electric field intensity due to no absorption.

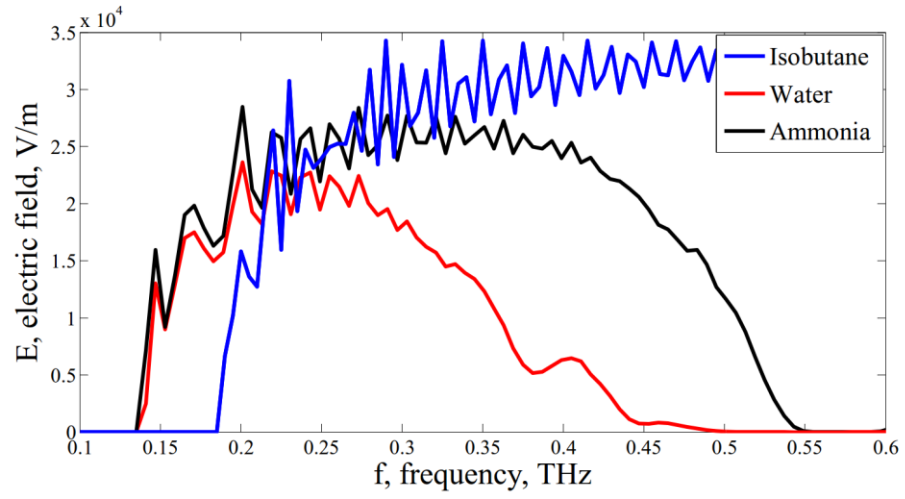


Figure 22. Electric field for 10mm long pipe.

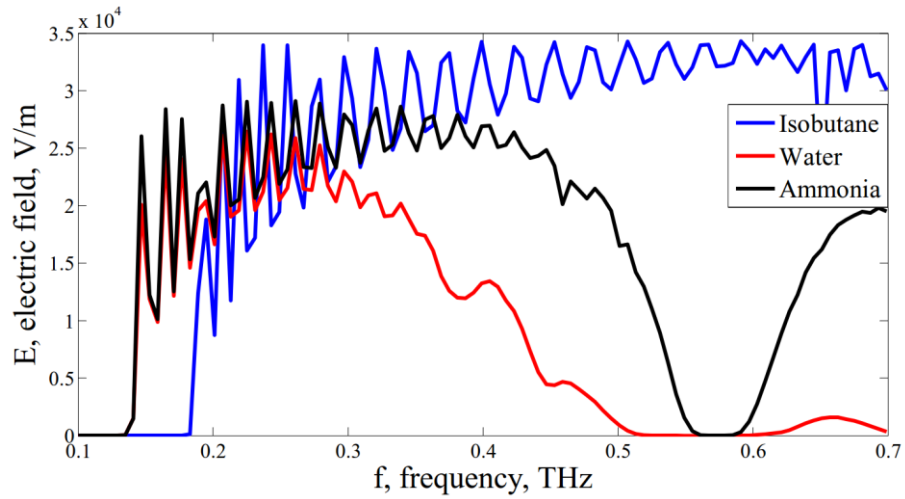


Figure 23. Electric field for 5mm long pipe.

6. CONCLUSIONS

In this thesis, performance evaluation of joint cooling and information transmission system for on-board communications in the THz frequency band is investigated. The system design provided both cooling and transmission functionalities is developed. The terahertz frequency range, 0.1 – 10 THz, is selected due to its attractive properties. The cooling is performed utilizing special refrigerant which does not have absorption lines in the considered frequency band ensuring the best possible propagation conditions. Two critical decisions – the choice of the cooling medium and casing material – are made.

In Chapter 2, the architecture of the proposed system is elaborated. The totally new design for the laptop motherboard is suggested and compared with existing wired and wireless communications architectures in addition with cooling system. Such design represents special heat pipes made from metal and with cooling substance inside. The heat pipes are going through the number of major hardware components (CPU, GPU, SDRAM) and represent point-to-point communications. In addition, detailed scheme is provided from the point of cooling system view. This scheme takes advantages of water-cooling system and conventional heat pipes. Finally, properties of a piece of a pipe are described for further cooling and transmission analysis.

The properties of the terahertz radiation are described in Chapter 3. This includes the position of the THz frequencies in the spectrum and general properties according to it. The major properties of the THz waves including absorption, path loss and molecular noise are considered. Finally, communications parameters such as capacity and SNR are explored.

Chapter 4 investigates material properties of the heat pipe including cooling medium and casing material. Isobutane is identified to be the most suitable refrigerant for the proposed application. This medium does not have any absorption lines in the considered frequency band, is characterized by the highest boiling point out of all refrigerants, and does not severely affect environment including ozone layer and global warming. For casing, metals are the best materials as they are characterized by high reflectivity allowing for heat pipe to serve as a waveguide. Further, taking into account the need for good thermal conductivity and competitive price, copper is chosen for the casing.

Finally, in Chapter 5, software calculations and simulations have been conducted to analyze the proposed design. Calculations for cooling evaluation have been done in MATLAB using the presented in Section 5.1 equations. The cooling performance was

analyzed using classic heat transfer theory. Further, signal propagation performance in the specified heat pipes have been estimated using COMSOL Multiphysics showing that these pipes can actually serve as waveguides. The potential rate performance of the system could achieve hundreds of gigabits per second due to extremely wide bandwidth and short on-board distances. The further research in this area could be the development of the signal propagation model for the specified environment and precise systems performance assessment in terms of capacity and achievable data rate. Besides, the detailed design of the system including transmitters and receivers with real parameters could be the scope of further research work.

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